LIFE-CYCLE COST ASSESSMENT FOR FRP STRUCTURES

Itaru Nishizaki
Advanced Materials Research Team, Public Works Research Institute, Japan

ABSTRACT

This report discusses recent examples of the application of LCCA on FRP structures in Japan, and considers the necessary conditions for the adoption of FRP structural materials. The results shows that the cost of producing the FRP structures was around 50% - 100% more than a conventional structures, however lighter FRP structure enables savings on substructure and installation cost, and the overall initial cost compares favorably with the conventional structures. Where the initial costs are roughly equivalent and the structure is to be used in a high corrosive environment, ongoing maintenance costs are lower as a result the overall LCC will be lower.

Keywords: life-cycle cost assessment, FRP, bridge, hydraulic gate.

1 INTRODUCTION

Japanese infrastructure is highly vulnerable to steel corrosion because the islands of Japan are surrounded by sea, and also because of the use of de-icing salt in snowy regional areas. Many attempts to combat corrosion have been used, including advanced anti-corrosion systems. The use of non-corrosive structural materials has long been considered the most promising solution to this problem. FRP is a leading example of a non-corrosive material.

However, FRP is not necessarily the optimum structural material for all conditions; at present it is regarded more as a special alternative in cases where ordinary materials cannot be used. We need to eliminate barriers preventing the widespread adoption of FRP structural materials. Life-Cycle Cost Assessment (LCCA) is one such approach. The main benefit of FRP structural materials is the lower LCCA through improved durability and corrosion resistance. LCCA represents an effective approach in this regard. This report discusses recent examples of the application of LCCA on FRP structures in Japan, and considers the necessary conditions for the adoption of FRP structural materials.

2 RECENT EXAMPLES OF LCCA ON FRP STRUCTURES IN JAPAN

2.1 LCCA based on Okinawa Road Park Bridge

Erected in March 2000, the Okinawa Road Park Bridge (see **Figure 1**) was the first FRP pedestrian bridge built in Japan; prior to this the only FRP bridges were experimental structures and trial models. The Okinawa Road Park Bridge is a two-span girder bridge with GFRP C-girders. Measuring 37.8 meters in length, it is a public pedestrian bridge spanning an existing vehicle roadway. The original design was for a PC bridge, but lightweight FRP was chosen instead due to concerns about sea salt corrosion from the surrounding seas as well as poor ground conditions. The bridge was heralded as the first genuine FRP trial in Japan which would demonstrate the future potential of this material. For this reason, an LCCA of the FRP bridge compared to conventional PC bridge materials was not performed at the time.

Figure 1: Okinawa Road Park Bridge
(The first all FRP pedestrian bridge in Japan, Okinawa Prefecture, 2000)

The LCCA based on the Okinawa Road Park Bridge was conducted shortly after construction by

Table 1: Life-Cycle Cost Assessment of Okinawa Road Park Bridge[1)]

	CASE 1	CASE 2	CASE 3		CASE 4	CASE 5
Main concept	Single span deck girder bridge with hollow PC beams	CASE 1 with coated reinforcing bars & PC tendons	CASE 2 with surface coating		Two span FRP girder bridge with GFRP C-girders	CASE 4 using modified handrails and joints on main girders
			Repair interval: 15 years	Repair interval: 30 years		
Initial cost of superstructure	48,240	50,620	54,370		73,600	62,350
Initial cost of substructure	10,130	10,130	10,130		6,910	6,910
Total initial costs	58,370	60,750	64,500		80,510	69,260
Maintenance cost (30 years)	24,500	0	18,000	9,000	6,000	3,500
Maintenance cost (50 years)	42,500	0	27,000	9,000	10,000	3,500
Maintenance cost (100 years)	69,500	24,500	54,000	27,000	20,000	7,000
50-year LCC	100,870	60,750	91,500	73,500	90,510	72,760
100-year LCC	127,870	85,250	118,500	91,500	100,510	76,260

the Japan Society of Civil Engineers[1)], in conjunction with a Life Cycle Assessment (LCA). The actual costs associated with construction of the bridge include a battery of technical investigations, tests and experiments, since this was the first FRP bridge ever built in Japan. For the purpose of the LCCA, then, the construction costs were recalculated based solely on the actual design specifications. Construction costs were also calculated using the design specifications for the original PC bridge design in order to provide a comparison value. Several of the stainless steel bolts on the FRP bridge were replaced after about five years due to the highly corrosive environmental conditions. This was used as the basis of the maintenance costs for the FRP bridge.

Table 1 shows the results of the LCCA. Although the life-cycle cost of the most economical version of the PC bridge is actually lower in some cases, it is clear that the FRP bridge can be made very cost-competitive through savings in certain areas: for instance, the use of bolts with better corrosion resistance would reduce maintenance costs, while less expensive joints and railings (chosen primarily for aesthetic reasons) could be used. The FRP bridge tends to be more economically viable in the long term, and is clearly superior in a long-term scenario involving harsh environmental conditions. .

2.2 LCCA on Jitenshado-13-go bridge [2)]

After the Okinawa Road Park Bridge in 2000, it was some time before the next FRP bridge appeared in Japan. During this period, much attention was given to the task of trying to reduce initial construction costs based on the Okinawa Road Park Bridge design. Finally in March 2008, a single-span FRP girder bridge named Jitenshado-13-go bridge (13th bridge of the Bicycle Path) was built on a coastal bicycle path in Hakui, Ishikawa prefecture. The bridge is 11.3 meters long with an effective width of 3.5 meters, and is notable for the use of pultruded FRP with no stiffener (see **Figure 2**).

Figure 2: Jitenshado-13-go bridge (Hakui, Ishikawa Pref., 2008)

Table 2: Life-Cycle Cost Assessment of Jitenshado-13-go bridge [2)]

Type of bridge		Single span FRP girder bridge	Single span steel girder bridge with H beams	Single span PC girder bridge with slab type T beams
Initial cost	Superstructure	14,500,000 JPY	8,900,000 JPY	9,600,000 JPY
	Substructure	2,000,000 JPY	5,000,000 JPY	5,000,000 JPY
Maintenance cost		0 JPY	2,900,000 JPY	2,400,000 JPY
LCC for 50 years		16,500,000 JPY	16,800,000 JPY	17,000,000 JPY
Dead load of superstructure		43 kN	158 kN	215 kN
Evaluation	Economic point	1.000	1.019	1.030
	Execution	Mostly manufactured at factory; simple to execute	Requires more work in situ	Simpler than steel bridge to execute
	Structural	Good earthquake-proof performance	Smaller substructure load than PC bridge	High rigidity = good serviceability
	Maintenance	Highly resistant to corrosion	Requires regular repainting	Requires regular repainting
	Others	Requires minor changes to substructure	Requires replacement of substructure	Requires replacement of substructure
Total evaluation		◎	△	○

Note: Estimated costs only

The previous wooden bridge was in need of replacement due to corrosion of the wooden joins. Since the bicycle path is used by schoolchildren, construction was completed quickly during the spring school holiday period.

When choosing the type of bridge, the client conducted an LCCA comparing FRP with conventional materials.[2)] **Table 2** shows the results of the comparison between the FRP bridge and steel bridge and PC bridges of equivalent size. The initial superstructure cost of the FRP bridge was ¥14.5 million, about 50% more than the steel and PC alternatives; however the latter bridge types had three to four times the dead load and required substantial substructure reinforcement. When both superstructure and substructure were taken into account, the FRP bridge was only about 20% more expensive; when ongoing maintenance costs were factored in as well, the life-cycle cost was roughly the same. Considering the relative speed and simplicity of construction and the superior resistance to earthquake movement and corrosion, the client concluded that an FRP bridge was a more suitable choice overall.

2.3 LCCA on FRP hydraulic gates[3)]

FRP is also used in other forms of public infrastructure, such as hydraulic gates. FRP hydraulic gates have been supplied by a number of domestic manufacturers for over 40 years, and have clearly proven more resistant to corrosion than steel gates. However FRP gates are limited in terms of size and for this reason are little known in Japan. FRP hydraulic gates are used in very few locations, with only a handful installed every year.

Figure 3: FRP gates at Komagari dam (Ogasawara, 2007)

Table 3: Life-Cycle Cost Assessment of FRP Gates at Komagari dam [3)]

Units: x ¥1,000 unless otherwise indicated				
Gate type		FRP	Steel	
Weight		248 kg	720 kg	
Maintenance interval (years)		Replace seal rubbers: 10	Replace seal rubbers: 10 Repaint: 5 Replace gate: 20	Replace seal rubbers: 10 Repaint: 10 Replace gate: 40
Initial cost	Gate	18,024	9,561	9,561
	Installation	2,612	10,714	10,714
	Total	20,636	20,275	20,275
Maintenance cost	Repainting	0	1,700	1,700
	Replacement of seal rubbers and repainting	1,300	2,000	2,000
	Replacement of gate	0	15,839	15,839
LCC	15 years	21,936	25,675	22,275
	30 years	24,536	45,214	26,275
	50 years	27,136	66,453	44,114
Note			Based on original specifications	Estimates by the author

In 2007, FRP hydraulic gates were installed at Komagari Dam on behalf of Ogasawara-mura (jurisdiction of Tokyo), replacing the previous steel gates (see **Figure 3**). An LCCA was conducted and the results released into the public domain.[3)] A summary of the results is presented below.

Ogasawara-mura, an island in the Pacific ocean located about 1,000 km from Tokyo, is subject to highly corrosive conditions. The hydraulic gates are used on a water source dam. They replaced a set of steel gates with a width of 2.0 m and a height of 0.96 m, which were severely corroded. The FRP gates were required to be cheaper in terms of initial cost as well as life-cycle cost. Also, due to poor access to the site, the gates were transported by manual labor, so it was important that the gates could be installed relatively easily on site.

Table 3 shows the LCCA results. Although the FRP gates are nearly twice as expensive to make as the steel gates, the installation costs were barely 25%, so the initial costs were only marginally higher overall. The original steel gate specifications stipulate maintenance expenses including repainting every five years and replacement every 20 years, given the highly corrosive environment. On this basis, the life-cycle cost of steel gates is higher than FRP gates after 15 years, and more than double after 50 years. However the maintenance regime was considered too strict, so another estimate was calculated based on a low-maintenance scenario of repainting every ten years and replacement every 40 years. Even then, the life-cycle cost of steel gates is 60% higher than FRP gates after 50 years.

3 DISCUSSION

3. 1 Common aspects of LCCA of FRP structures

Based on the LCCA studies conducted on FRP structures to date, the following general conclusions can be made:

(1) The weight of the FRP structure is around 25% - 35% of the equivalent conventional structure.

(2) The cost of producing the FRP structure is around 50% - 100% more than a conventional structure.

(3) Where the lighter FRP structure enables savings on substructure and installation costs, the overall initial cost compares favorably with the conventional structure, being about the same or at most 20% more.

(4) Where the initial costs are roughly equivalent and the structure is to be used in a highly corrosive environment, ongoing maintenance costs are lower and as a result the overall LCC will be lower.

The conditions outlined above are not considered to be particularly unusual; these sorts of conditions are encountered quite often. In the future it is likely that FRP structures will increasingly be found in LCCA studies to be the best option in such conditions.

3.2 FRP maintenance cost assumptions in LCCA

The majority of LCC studies conducted to date on FRP structures have assumed low maintenance costs, but this assumption may not necessarily be correct. The author decided to investigate the validity of the assumption, as described below.

(1) Study of literature

The Okinawa Road Park Bridge, the first FRP bridge built in Japan, has been in use for nine years now. Brief reports on the durability and extent of deterioration of the bridge have been found in existing literature. Although there was no evidence of major damage or deterioration in the FRP structure itself, many of the stainless steel (SUS316) bolts were in an advanced state of corrosion due to the harsh environment and had to be replaced. FRP bridges often employ bolts and joints made from stainless steel rather than FRP. These clearly require additional corrosion protection and maintenance, and consideration should be given to the use of more corrosion-resistant materials, especially on parts that are difficult to replace.

Keller[4)] and Bank[5)] have studied the durability of similar FRP bridges and structures. Keller reports on the Pontresina Bridge, an FRP truss pedestrian bridge erected in Switzerland in 1997. The Pontresina Bridge is designed for use by skiers during the winter months; during the summer it is kept in storage. An in-depth deterioration analysis was conducted on the bridge whilst in storage in the summer of 2005, eight years after construction. The analysis included a repeat of the load tests performed at the time of construction. Although the overall performance characteristics had been retained, there was evidence of damage to flange tips as well as cracking in some areas. This was thought to be largely attributable to localized impacts occurring during the initial construction period and/or subsequent transportation, as well as incorrect storage procedures. Keller concluded that the GFRP structure would have exhibited the expected level of durability had it been treated in the appropriate manner.

Bank reports on the results of a durability study on a roof over the entrance to a university hall in the United States, which was built in 1994 using FRP bridge materials and techniques. The study was conducted 12 years after construction. The structure was found to be in good condition overall, although the following forms of deterioration were identified: surface color fading of FRP material; corrosion of galvanized nuts and bolts; localized cracking in the fiber direction around bolt joints; and fiber blooming. The study recommended using stainless steel rather than galvanized bolts and coating the structure with polyurethane coating or equivalent.

The above studies of real-life structures suggest that overall durability should not be an issue when the structure is maintained in the appropriate manner. The limited deterioration that does occur can be managed easily through appropriate treatment.

(2) Durability evaluation of FRP hydraulic gates

FRP bridges have a relatively short history in Japan. The first FRP bridge model was demonstrated only ten years ago. We have far longer experience in other applications of FRP in corrosive environments, namely, FRP hydraulic gates. More than two hundred FRP hydraulic gates are still in use in Japan, with the oldest having been installed over 40 years ago. For the purpose of this paper, the author studied the durability of a gate that has been in use for 35 years[6)].

For the durability study, the author identified and recovered an FRP gate body that had been used as a sluice gate on an agricultural waterway for over 35 years (**Figure 4**). **Table 4** lists key statistics for the recovered FRP gate. Tensile properties were evaluated using the main girder channel and the skin plate of the gate body.

Figure 4: FRP gate in use for 35 years

Figure 5 shows the outline of the gate body. Specimens for the tensile tests were taken from the lower main girder and two sections of the skin plate in the submerged area and the non-submerged area. In the absence of initial data for the gate body, the author analyzed the layering system of the FRP material and ordered new FRP test pieces with the same layering system as the original FRP gate, from the original manufacturer. The new test pieces were used to generate base data for the initial mechanical properties of the gate body, and were also subject to tensile tests.

Table 4: Key statistics of FRP gate

Constructed	Prior to 1969
In service	Over 35 years
Type	Slide gate
Dimensions	1.15 m x 1.00 m
FRP sections	Gate body, gate stop
Molding method	Hand lay-up
Operating conditions	Full-time operation
Water absorption damage	N/A
Erosion damade	N/A
Deterioration	Water stains, discoloration

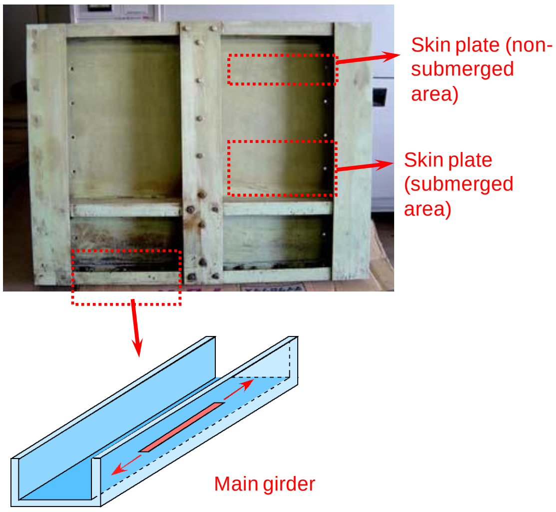

Figure 5: Tested specimens obtained from FRP gate (body section)

Table 5: Tensile tests on recovered gate and new FRP pieces

	Recovered gate (Non-submerged area)	Recovered gate (Submerged area)	New FRP
Tensile strength (MPa)	148.3	150.0	166.8
Tensile modulus (GPa)	16.1	17.1	16.0

Note: Values are averages of five repetitions

Table 5 shows the results. In all cases, it was found that the mean tensile strength and modulus values of the recovered gate were virtually identical to those of the new FRP specimens.

The results suggest that, while FRP structures used in civil engineering applications do deteriorate to some extent, proper design should be able to prevent structural problems. Thus, in future LCCA studies, it should be acceptable to assume a low level of maintenance and upkeep expenses.

4 FUTURE ISSUES

The LCCA is based on three types of costs: initial costs, maintenance costs and disposal costs. Disposal costs are more difficult to calculate and have been omitted in this paper, but at some point disposal costs will need to be incorporated into calculations. Landfill disposal costs for FRP are roughly the same as for other materials, whereas incineration would significantly increase the LCA. Thought should be given to viable alternatives in the form of reuse and/or recycling.

Although we have established that FRP material itself is highly durable, we do not have enough information on the durability of FRP when used in combination with other materials. The stainless steel bolts on the FRP bridge in Okinawa already require replacement, and there are still many unknowns in relation to the behavior of adhesives used between FRP pieces and between FRP and other materials such as steel and concrete. Further research is required in this area.

References

1) Itaru Nishizaki, Nobufumi Takeda, Yoshio Ishizuka and Takumi Shimomura, "A Case Study of Life Cycle Cost based on a Real FRP Bridge", Proceedings of the Third International Conference on FRP Composites in Civil Engineering (CICE2006), pp.99-102 (December 2006).

2) Kazutoshi Nakashima, Hiromichi Yasunami and Hiroyuki Hosonuma, "Design, manufacture, and erection of Jitenshado-13-go bridge made of FRP", Proceedings of The Third Symposium on FRP Hybrid Structures and Bridges, pp.183-186 (July 2009) (in Japanese).

3) Hideki Hibi, Hiroyuki Iwamoto, Yoshinori Fujimoto and Hitoshi Furukawa, "Construction Example of the FRP Management Bridge and FRP Hydraulic Gates in the Detached Island", Proceedings of The Third Symposium on FRP Hybrid Structures and Bridges, pp.169-174 (July 2009) (in Japanese).

4) T. Keller, Y. Bai and T, Vallee, "Long-Term Performance of the Pontresina GFRP Pedestrian Bridge", Proceedings of the Third International Conference on Durability and Field Applications of FRP Composites for Construction, pp.345-352 (May 2007).

5) L. C. Bank, T. R. Gentry, G. E. Johansen, R. Wilson and R. Weil, "Long-Term Performance of a Pultruded Light Frame Canopy Structure", Proceedings of the Third International Conference on Durability and Field Applications of FRP Composites for Construction, pp.91-100 (May 2007).

6) Tomonori Tomiyama and Itaru Nishizaki, "Applicability of Fiber Reinforced Plastics to Hydraulic Gates", Proceedings of the Third International Conference on FRP Composites in Civil Engineering (CICE2006), pp.453-456 (2006).